SOAP – Spherical Overdensity and Aperture Processor

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1 Introduction

SOAP computes different types of properties, depending on how particles are included (by radius, in projection...). For all types, we use the halo membership and centre of potential as determined by the input halo catalogue. This documentation is generated using the SOAP parameter file, and so the properties listed reflect those present in the current run of SOAP, rather than all possible properties.

2 Property types

Subhalo quantities (SH) are computed for each subhalo identified by the halo finder, irrespective of whether it is a field halo or a satellite (or even satellite of satellite and so on). They include all particles that they halo finder has determined are bound to the subhalo. Subhalo properties are contained within the group BoundSubhalo in the output file.

Exclusive sphere quantities (ES) are similar to subhalo quantities, but they include only the particles that are bound to the subhalo, and apply an additional radial cut (aperture). We use eight different aperture radii (10, 30, 50, 100, 300, 500, 1000, 3000 kpc), so that every (sub-)halo has eight of these. Exclusive sphere properties are contained within a group ExclusiveSphere/XXXkpc, where XXX is the corresponding aperture radius.

Inclusive sphere quantities (IS) use the same physical aperture radii as the exclusive sphere quantities, but include all particles within the radius, regardless of their membership status. They are stored within a group InclusiveSphere/XXXkpc.

Exclusive projected quantities (EP) are similar to exclusive sphere quantities, except that their aperture filter is applied in projection, and this for independent projections along the x-, y- and z-axis. Along the projection axis, we do not apply any radial cut, so that the depth corresponds to all particles bound to the (sub-)halo. With four projected aperture radii (10, 30, 50, 100 kpc), we then have twelve sets of projected aperture quantities for each (sub-)halo. Projected aperture quantities are stored in a group named ProjectedAperture/XXXkpc/projP, where XXX is the corresponding aperture radius, and P corresponds to a particular projection direction (x, y or z).

Spherical overdensity properties (SO) are fundamentally different from the three other types in that their aperture radius is determined from the density profile and is different for different halos. They always include all particles within a sphere around the centre of potential, regardless of halo membership. The radius is either the radius at which the density reaches a certain target value (50 crit, 100 crit, 200 crit, 500 crit, 1000 crit, 2500 crit, 200 mean, BN98) or a multiple of such a radius (5xR 500 crit). Details of the spherical overdensity calculation are given at the end of this document. Spherical overdensities are only computed for centrals, i.e. field halos. The inclusive sphere quantities are stored in a group SO/XXX, where XXX can be either XXX_mean for density multiples of the mean density, XXX_crit for density multiples of the critical density, BN98 for the overdensity definition of Bryan & Norman (1998), and YxR_XXX_ZZZ for multiples of some other radius (e.g. 5xR_2500_mean). The latter can only be computed after the corresponding density multiple SO radius has been computed. This is achieved by ordering the calculations.

InputHalos Some properties are directly copied from the original halo catalogue that was passed to SOAP. These are stored in a separate group, **InputHalos**.

SOAP Some properties are computed by SOAP using the other halo properties present in the catalogue. These are stored in a separate group, SOAP. This is just done for convenience; these quantities can be computed from the SOAP output alone.

The table below lists all the groups in the output file which containing datasets. Note that there will be three groups (x, y or z) for each ProjectedAperture variation. Each halo variation can have a filter applied to it. If a halo does not satisfy the filter then the variation will not be calculated for that halo. More information on filters can be found in the next section.

Group name (HDF5)	Group name (swiftsimio)	Inclusive?	Filter
BoundSubhalo	bound_subhalo	×	-
S0/200_crit	<pre>spherical_overdensity_200_crit</pre>	1	-
SO/50_crit	<pre>spherical_overdensity_50_crit</pre>	1	general
S0/100_crit	<pre>spherical_overdensity_100_crit</pre>	1	general
S0/200_mean	<pre>spherical_overdensity_200_mean</pre>	1	-
S0/500_crit	<pre>spherical_overdensity_500_crit</pre>	1	-
SO/5xR_500_crit	<pre>spherical_overdensity_5xr_500_crit</pre>	1	general
S0/1000_crit	<pre>spherical_overdensity_1000_crit</pre>	1	general
S0/2500_crit	<pre>spherical_overdensity_2500_crit</pre>	1	general
SO/BN98	<pre>spherical_overdensity_bn98</pre>	1	general
ExclusiveSphere/10kpc	exclusive_sphere_10kpc	×	-
ExclusiveSphere/30kpc	exclusive_sphere_30kpc	×	-
ExclusiveSphere/50kpc	exclusive_sphere_50kpc	×	-
ExclusiveSphere/100kpc	exclusive_sphere_100kpc	×	-
ExclusiveSphere/300kpc	exclusive_sphere_300kpc	×	-
ExclusiveSphere/500kpc	exclusive_sphere_500kpc	×	general
ExclusiveSphere/1000kpc	exclusive_sphere_1000kpc	×	general
ExclusiveSphere/3000kpc	exclusive_sphere_3000kpc	×	general
InclusiveSphere/10kpc	inclusive_sphere_10kpc	1	-
InclusiveSphere/30kpc	inclusive_sphere_30kpc	1	-
InclusiveSphere/50kpc	inclusive_sphere_50kpc	1	-
InclusiveSphere/100kpc	inclusive_sphere_100kpc	1	-
InclusiveSphere/300kpc	inclusive_sphere_300kpc	1	-
InclusiveSphere/500kpc	inclusive_sphere_500kpc	1	general
InclusiveSphere/1000kpc	inclusive_sphere_1000kpc	1	general
InclusiveSphere/3000kpc	inclusive_sphere_3000kpc	1	general
ProjectedAperture/10kpc/projP	projected_aperture_10kpc_projP	×	general
ProjectedAperture/30kpc/projP	projected_aperture_30kpc_projP	×	general
ProjectedAperture/50kpc/projP	projected_aperture_50kpc_projP	×	general
ProjectedAperture/100kpc/projP	projected_aperture_100kpc_projP	×	general
SOAP	soap	-	_
InputHalos	input_halos	-	-
InputHalos/HBTplus	input_halos_hbtplus	-	-
InputHalos/FOF	input_halos_fof	-	-

3 Property categories

Halo properties only make sense if the subhalo contains sufficient particles. Halo finders are often run with a configuration that requires at least 20 particles for a satellite subhalo. However, even for those particle numbers, a lot of the properties computed by SOAP will be zero (e.g. the gas mass within a 10 kpc aperture), or have values that are outliers compared to the full halo population because of undersampling. We can save a lot of disk space by filtering these out by applying appropriate cuts. Filtering means setting the value of the property to NaN; HDF5 file compression then very effectively reduces the data storage required to store these properties, while the size of the arrays that the end user sees remains unchanged. Evidently, we can also save on computing time by not computing properties that are filtered out.

Since different properties can have very different requirements, filtering is done in categories, where each category corresponds to a set of quantities that are filtered using the same criterion. Inclusive, exclusive or projected quantities with different aperture radii (or overdensity criteria) can be used to create profiles. In order for these profiles to make sense, we have to apply a consistent cut across all the different aperture radii (or overdensity criteria) for the same subhalo property type. Or in other words: the quantities for an inclusive sphere with a 10 kpc aperture radius will use the same filter mask as the quantities of the inclusive sphere with a 3000 kpc aperture radius, even though the latter by construction has many more particles.

Basic quantities (basic) are never filtered out, and hence are calculated for all objects in the input halo catalogue.

General quantities (general) use a filter based on the total number of particles bound to the subhalo.

Gas quantities (gas) use a filter based on the number of gas particles bound to the subhalo.

DM quantities (dm) use a filter based on the number of DM particles bound to the subhalo.

Stellar quantities (star) use a filter based on the number of star particles bound to the subhalo.

Baryon quantities (baryon) use a filter based on the number of gas and star particles bound to the subhalo.

Note that there are no quantities that use a BH or neutrino particle number filter.

The particle number thresholds are set in the parameter file. The different categories are summarised in the table below.

 $\begin{array}{lll} \mbox{Name} & \mbox{criterion} \\ \hline \mbox{basic} & \mbox{(all halos)} \\ \mbox{general} & N_{\rm gas} + N_{\rm dm} + N_{\rm star} + N_{\rm BH} \geq 100 \\ \mbox{gas} & N_{\rm gas} \geq 100 \\ \mbox{dm} & N_{\rm dm} \geq 100 \\ \mbox{star} & N_{\rm star} \geq 100 \\ \mbox{baryon} & N_{\rm gas} + N_{\rm star} \geq 100 \end{array}$

4 Overview table

The table below lists all the properties that are computed by SOAP when run in HYDRO mode. For dark matter only (DMO) mode only the properties colored violet/purple are computed. This table is automatically generated by SOAP from the source code, so that all names, types, units, categories and descriptions match what is actually used and output by SOAP. For each quantity, the table indicates for which halo types the property is computed. Superscript numbers refer to more detailed explanations for some of the properties and match the numbers in the next section. If swiftsimio has been used to load a catalogue then the fields names are in snake_case rather than CamelCase, e.g. CentreOfMass becomes centre_of_mass.

Note that quantities are given in the base units of the simulation snapshot. The attributes of each SOAP dataset contains all the relevant meta-data to convert between physical and co-moving units, i.e. information about how the quantity depends on the scale-factor, and what the conversion factor to and from CGS units is. All quantities are h-free. The conversion of the base units to CGS is given by:

 Unit
 CGS conversion

 L
 3.086e+24 cm

 M
 1.988e+43 g

 t
 3.086e+19 s

 T
 1 K

For example, a property whose units are listed as M/t will have units of velocity, where 1 M/t = 1 km/s. The scale factor is explicitly included for comoving properties (e.g. the units of HaloCentre are aL)

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										
BlackHolesDynamicalMass Total BH dynamical mass.	1	float32	М	1	1	1	1	1	basic	$1.36693{\rm e}{\rm 10} \rightarrow 1.367{\rm e}{\rm 10}$
BlackHolesSubgridMass Total BH subgrid mass.	1	float32	М	1	1	1	1	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
$\begin{array}{c} \text{CentreOfMass}^1 \\ \text{Centre of mass.} \end{array}$	3	float64	a · L	1	1	1	1	1	basic	1 pc accurate
CentreOfMassVelocity ¹ Centre of mass velocity.	3	float32	$\mathbf{a}\cdot\mathbf{L}/\mathbf{t}$	1	1	1	1	1	basic	$0.1~{\rm km/s}$ accurate
Concentration ² Halo concentration assuming length	1 g an NFV	float32 V profile.	dimensionless Minimum part	× icle r	× adius	\mathbf{x} set t	× o soft	✓ ening	basic	$1.36693e10 \rightarrow 1.367e10$
ConcentrationUnsoftened Halo concentration assuming	1 an NFW	float32 7 profile. 1	dimensionless No particle softe	× ning.	×	×	×	1	basic	$1.36693e10 \rightarrow 1.367e10$
DarkMatterConcentration ² Concentration of dark matter set to softening length	1 particles	float32 5 assuming	dimensionless g an NFW profil	× e. Mi	× nimur	× n par	× ticle r	✓ adius	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
DarkMatterConcentration- Unsoftened Concentration of dark matter	1 r particle	float32 s assumin	dimensionless g an NFW profi	X le No	X	X	X	🗸	basic	$1.36693{\rm e}{\rm 10} \rightarrow 1.367{\rm e}{\rm 10}$
Halo concentration assuming DarkMatterConcentration ² Concentration of dark matter set to softening length DarkMatterConcentration- Unsoftened Concentration of dark matter	an NFW 1 particles 1 r particle	7 profile. 1 float32 s assuming float32 s assumin	No particle softe dimensionless g an NFW profil dimensionless g an NFW profi	e. Mir × k ×	× nimur ×	× n par × icle s	× ticle r × ofteni	✓ adius ✓	basic basic	$1.36693e10 \rightarrow 1.367e1$ $1.36693e10 \rightarrow 1.367e1$

Name Description	Shape	Type	Units	SH	ES	IS	ΕP	SO	Category	Compression
DarkMatterMass Total DM mass.	1	float32	М	1	1	~	1	1	basic	$1.36693e10 \to 1.367e10$
EncloseRadius Radius of the particle furthe	1 st from tl	float32 he halo ce	$\mathbf{a} \cdot \mathbf{L}$ entre	1	×	×	×	×	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
GasMass Total gas mass.	1	float32	М	1	1	1	1	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
GasMassFractionInMetals ³ Total gas mass fraction in m	1 etals.	float32	dimensionless	1	1	1	×	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
HalfMassRadiusStars ⁴ Stellar half mass radius.	1	float32	$\mathbf{a} \cdot \mathbf{L}$	1	1	1	1	×	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
MaximumCircularVelocity ⁵ Maximum circular velocity v	1 vhen acco	float32 ounting for	L/t r particle softeni	✓ ng ler	\mathbf{X}	×	×	×	basic	$1.36693e10 \rightarrow 1.367e10$
MaximumCircularVelocityRadius- Unsoftened ⁵	1	float32	a·L	 I 	×	×	×	×	basic	$1.36693e10 \rightarrow 1.367e10$
Radius at which MaximumC	Sircular Ve	locityUns	oftened is reache	ed.						
$\begin{array}{l} Maximum Circular Velocity-\\ Unsoftened^5 \end{array}$	1	float32	L/t	1	×	×	×	×	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$

Maximum circular velocity when not accounting for particle softening lengths.

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Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	IS	\mathbf{EP}	SO	Category	Compression
Description										
MostMassiveBlackHoleID ID of most massive black hol	1 le.	uint64	dimensionless	1	1	1	1	1	basic	Store less bits
MostMassiveBlackHoleMass ⁶ Mass of most massive black l	1 hole.	float32	М	1	1	1	1	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
NoiseSuppressedNeutrinoMass ⁷ Noise suppressed total neutri	1 ino mass.	float32	М	×	×	×	×	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
NumberOfBlackHoleParticles Number of black hole particl	1 es.	uint32	dimensionless	1	1	1	1	1	basic	no compression
NumberOfDarkMatterParticles Number of dark matter parti	1 icles.	uint32	dimensionless	1	1	1	1	1	basic	no compression
NumberOfGasParticles Number of gas particles.	1	uint32	dimensionless	1	1	1	1	1	basic	no compression
NumberOfNeutrinoParticles Number of neutrino particles	1 3.	uint32	dimensionless	×	×	X	×	1	basic	no compression
NumberOfStarParticles Number of star particles.	1	uint32	dimensionless	1	1	1	1	1	basic	no compression
RawNeutrinoMass ⁷ Total neutrino particle mass.	1	float32	М	×	×	×	×	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$

_	Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
	SORadius Radius of a sphere satisfying	1 a spheri	float32 cal overde	a · L ensity criterion.	×	×	×	×	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
	StarFormationRate ⁸ Total star formation rate.	1	float32	M/t	1	1	1	1	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
	StarFormingGasMassFractionIn- Metals ^{8,3}	1	float32	dimensionless	1	1	1	×	1	basic	$1.36693{\rm e}10 \to 1.367{\rm e}10$
	Total gas mass fraction in me	etals for	gas that i	s star-forming.							
	StellarMass Total stellar mass.	1	float32	М	1	1	1	1	1	basic	$1.36693e10 \rightarrow 1.367e10$
	StellarMassFractionInMetals Total stellar mass fraction in	1 metals.	float32	dimensionless	1	1	1	×	1	basic	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
_	TotalMass Total mass.	1	float32	М	1	1	1	1	1	basic	$1.36693e10 \rightarrow 1.367e10$
_	BlackHolesLastEventScalefactor Scale-factor of last AGN even	1 nt.	float32	dimensionless	1	1	1	1	1	general	$1.36693e10 \rightarrow 1.367e10$
	ComptonY ⁹ Total Compton y parameter.	1	float64	L^2	×	×	×	×	1	general	$1.36693{\rm e}10 \to 1.367{\rm e}10$

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										
ComptonYWithoutRecent- AGNHeating ⁹ Total Compton y parameter.	1 Exclude	float64 es gas tha	L ² t was recently	×	× by A0	× GN.	×	1	general	$1.36693 \mathrm{e}10 ightarrow 1.367 \mathrm{e}10$
DopplerB ¹⁰ Kinetic Sunyaey-Zel'dovich e lightcone observer.	1 effect, ass	float32 uming a l	a· ine of sight tov	× wards tł	× ne pos	\mathbf{x}	\times of the	✓ e first	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
GasComptonYTemperature ¹¹ ComptonY-weighted mean g	1 as tempe	float32 rature.	Т	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
GasComptonYTemperatureCore- Excision ^{12,11} ComptonY-weighted mean g	1 as tempe	float32 rature, ex	T cluding the im	× ner exci	× sed co	×	×	1	general	$1.36693{\rm e}10 \to 1.367{\rm e}10$
GasComptonYTemperature- WithoutRecentAGNHeating ¹¹ ComptonY-weighted mean g AGN.	1 gas temp	float32 erature, o	T excluding gas	that wa	× as rec	×	×	🖌 ed by	general	$1.36693 e10 \rightarrow 1.367 e10$
GasComptonYTemperature- WithoutRecentAGNHeatingCore- Excision ^{12,11} ComptonY-weighted mean g	1 as tempe	float32 rature, ex	T ccluding the in	× ner exci	× ised c	× ore a	× nd gas	✓ s that	general	$1.36693e10 \rightarrow 1.367e10$

was recently heated by AGN.

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	float32	dimensionless	×	1	,				
	floot 20			•	V	X	1	general	$1.36693e10 \rightarrow 1.367e1$
	110at52	dimensionless	×	1	1	×	1	general	$1.36693e10 \rightarrow 1.367e1$
rature	float32	Т	1	1	1	×	1	general	$1.36693e10 \to 1.367e1$
rature	float32 , excludir	T ng the inner excis	× sed co	× re.	×	×	1	general	$1.36693e10 \to 1.367e1$
	float32	Т	1	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e1$
rature	, excludin	ng cool gas with a	a temj	peratu	re b	elow 1	e5 K.		
	float32	Т	1	×	×	×	1	general	$1.36693\mathrm{e}10 \rightarrow 1.367\mathrm{e}1$
rature .GN.	, excludir	ng cool gas with	a tem	perat	ure b	elow 1	le5 K		
	float32	Т	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e1$
1 11	ature: rature: GN.	float32 ature, excludir float32 rature, excludir GN. float32	float32 T ature, excluding cool gas with a float32 T rature, excluding cool gas with GN. float32 T	float32 T ✓ sature, excluding cool gas with a temp float32 T ✓ rature, excluding cool gas with a tem GN. float32 T ×	float 32 T × × rature, excluding cool gas with a temperature float 32 T × × rature, excluding cool gas with a temperature GN. float 32 T × ×	float 32 T \checkmark X X stature, excluding cool gas with a temperature be float 32 T \checkmark X X rature, excluding cool gas with a temperature b GN. float 32 T X X X	float 32 T \checkmark X X X stature, excluding cool gas with a temperature below 1 float 32 T \checkmark X X X rature, excluding cool gas with a temperature below 1 GN. float 32 T X X X X	float32 T Image: X mark X mark X mark Image: X mark Imark Imark Imar	float 32TImage: Image: I

and gas that was recently heated by AGN.

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
$GasTemperatureWithoutCool-GasCoreExcision^{12}$	1	float32	Т	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Mass-weighted mean gas te K.	mperature	e, excludii	ng the inner exc	ised co	ore an	id gas	s belo	w 1e5		
$GasTemperatureWithoutRecent-AGNHeating^{13}$	1	float32	Т	1	1	1	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Mass-weighted mean gas te	mperature	e, excludir	ng gas that was	recent	y hea	ted b	oy AG	N.		
GasTemperatureWithoutRecent- AGNHeatingCoreExcision ¹² Mass-weighted mean gas te recently heated by AGN.	1 mperature	float32 e, excludi	T ng the inner exc	× eised c	× ore, a	× nd g	× as tha	✓ at was	general	$1.36693e10 \rightarrow 1.367e10$
HalfMassRadiusTotal ⁴ Total half mass radius.	1	float32	a · L	1	×	×	×	×	general	$1.36693 e10 \rightarrow 1.367 e10$
HotGasMass Total mass of gas with a ter	1 mperature	float32 e above 1e	М 5 К.	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
MassFractionExternal ¹⁴ Fraction of mass that is bou	1 ind to a s	float32 atellite ou	dimensionless itside this FOF	× group.	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
MassFractionSatellites ¹⁴ Fraction of mass that is bou	1 ind to a s	float32 atellite in	dimensionless the same FOF	× group.	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	IS	\mathbf{EP}	SO	Category	Compression
Description										
MostMassiveBlackHoleAccretion- Rate Gas accretion rate of most n	1 nassive bl	float32 ack hole.	M/t	1	1	1	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
MostMassiveBlackHoleLastEvent- Scalefactor Scale-factor of last AGN eve	1 nt for mo	float32 ost massiv	dimensionless e black hole.	1	1	1	1	1	general	$1.36693e10 \rightarrow 1.367e10$
MostMassiveBlackHolePosition Position of most massive bla	3 .ck hole.	float64	$\mathbf{a} \cdot \mathbf{L}$	1	1	1	1	1	general	1 pc accurate
MostMassiveBlackHoleVelocity Velocity of most massive bla	3 .ck hole r	float32 elative to	$\mathbf{a} \cdot \mathbf{L}/\mathbf{t}$ the simulation v	✓ volume	✓ e.	1	1	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
ProjectedTotalInertiaTensor- Noniterative	3	float32	L^2	Х	Х	×	1	×	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
2D inertia tensor computed to the halo centre. Diagonal comp calculated when we have more than	in a sing ponents an a 20 parti	le iteratic nd one of cles.	on from the tota f-diagonal value	l mass as (1	s distı ,1), (2	ributi 2,2),	on, re $(1,2)$.	elative Only		
ProjectedTotalInertiaTensor- ReducedNoniterative Reduced 2D inertia tensor correlative to the halo centre. Diagona	3 omputed al compo	float32 in a singl nents and	dimensionless e iteration from one off-diagonal	× the to l value	× otal m e as (1	× nass d 1,1),	\checkmark listrib $(2,2),$	$\begin{array}{c} \times \\ \text{ution,} \\ (1,2). \end{array}$	general	$1.36693e10 \rightarrow 1.367e10$
Only calculated when we have more	e than 20	particles								

 $\frac{13}{3}$

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										
SpectroscopicLikeTemperature ¹⁵ Spectroscopic-like gas tempe	1 erature.	float32	Т	X	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
$\begin{array}{l} {\rm SpectroscopicLikeTemperature-}\\ {\rm CoreExcision}^{12,15} \end{array}$	1	float32	Т	×	Х	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Spectroscopic-like gas tempe	erature. E	Excludes g	as in the inner ϵ	excised	l core					
${ m SpectroscopicLikeTemperature-} WithoutRecentAGNHeating^{15}$	1	float32	Т	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Spectroscopic-like gas tempe	erature. E	Exclude ga	s that was recen	tly he	eated	by A	GN			
SpectroscopicLikeTemperature- WithoutRecentAGNHeatingCore- Excision ^{12,15}	1	float32	Т	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
Spectroscopic-like gas temper gas in the inner excised core	rature. E	xclude gas	s that was recent.	ly hea	ted by	AGI	N. Exc	cludes		
SpinParameter ¹⁶ Bullock et al. (2001) spin pa	1 arameter.	float32	dimensionless	1	1	1	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
StarFormingGasMass ⁸ Total mass of star-forming g	1 jas.	float32	М	1	1	1	×	×	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
StarFormingGasMassFractionIn- Iron ^{8,3}	1	float32	dimensionless	×	1	1	×	×	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$

Total gas mass fraction in iron for gas that is star-forming.

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Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	IS	\mathbf{EP}	SO	Category	Compression
Description										
StarFormingGasMassFractionIn- Oxygen ^{8,3} Total gas mass fraction in o	1 xygen for	float32 gas that	dimensionless is star-forming.	×	1	1	×	×	general	$1.36693 e10 \rightarrow 1.367 e10$
ThermalEnergyGas ¹⁷ Total thermal energy of the	1 gas.	float64	$\frac{L^2 \cdot M}{t^2}$	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
TotalInertiaTensor 3D inertia tensor computed centre. Diagonal components and o Only calculated when we have more	6 iteratively one off-dia ce than 20	float32 y from the agonal tria) particles	L^2 total mass distangle as (1,1), (2	✓ ributio 2,2), (3	× on, rel 3,3), (\mathbf{X} lative $(1,2),$	$\begin{array}{c} \times \\ \text{to th} \\ (1,3), \end{array}$	× e halo (2,3).	general	$1.36693e10 \rightarrow 1.367e10$
TotalInertiaTensorNoniterative 3D inertia tensor computed to the halo centre. Diagonal comp (1,3), (2,3). Only calculated when	6 in a sing onents an we have 1	float32 cle iteration d one off- more than	L^2 on from the tota diagonal triangle 20 particles.	✓ al mass e as (1	× s distr l,1), (\mathbf{x} ributi 2,2),	$\begin{array}{c} \times \\ \text{ion, re} \\ (3,3), \end{array}$	\checkmark elative $(1,2),$	general	$1.36693e10 \rightarrow 1.367e10$
TotalInertiaTensorReduced Reduced 3D inertia tensor	6 computed	float32 iterative	dimensionless ly from the tota	✓ l mas	× s disti	× ributi	×	× elative	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$

to the halo centre. Diagonal components and one off-diagonal triangle as (1,1), (2,2), (3,3), (1,2),

(1,3), (2,3). Only calculated when we have more than 20 particles.

Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
6	float32	dimensionless	1	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
mputed i compone hen we l	in a single ents and c have more	e iteration from one off-diagonal t e than 20 partic	the to triangles.	otal m .e as (lass d $1,1),$	(2,2),	ution, $(3,3)$,		
3 ninosity	float64 in three	$\frac{\mathbf{L}^2 \cdot \mathbf{M}}{\mathbf{t}^3}$ bands.	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
3 ninosity	float64 in three b	$\frac{L^2 \cdot M}{t^3}$ bands. Excludes	× gas in	\mathbf{x} the in	×	×	✓ l core	general	$1.36693e10 \rightarrow 1.367e1$
3 sity in th	float64 rree band	$\frac{\mathbf{L}^2 \cdot \mathbf{M}}{\mathbf{t}^3}$ S.	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e1$
3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	1	general	$1.36693\mathrm{e}10 \rightarrow 1.367\mathrm{e}1$
sity in th	ree band	s. Excludes gas	in the	e inne	r exc	ised co	ore		
3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e1$
	Shape 6 mputed f compone hen we l 3 minosity 3 sity in th 3 sity in th 3	Shape Type 6 float32 mputed in a single components and co- hen we have more 3 float64 minosity in three 1 3 float64 ninosity in three band 3 float64 sity in three band 3 float64 sity in three band 3 float64	ShapeTypeUnits6float32dimensionlessmputed in a single iteration from components and one off-diagonal to hen we have more than 20 particle3float64 $\frac{L^2 \cdot M}{t^3}$ minosity in three bands.3float64 $\frac{L^2 \cdot M}{t^3}$ ninosity in three bands.3float64 $\frac{L^2 \cdot M}{t^3}$ sity in three bands.3float64 $\frac{L^2 \cdot M}{t^3}$ sity in three bands.3float64 $\frac{L^2 \cdot M}{t^3}$ sity in three bands.Excludes gas3float64 $\frac{L^2 \cdot M}{t^3}$	ShapeTypeUnitsSH6float32dimensionless\checkmark6float32dimensionless✓mputed in a single iteration from the to components and one off-diagonal triangle hen we have more than 20 particles.33float64 $\frac{L^2 \cdot M}{t^3}$ ×3float64 $\frac{L^2 \cdot M}{t^3}$ ×afloat64 $\frac{L^2 \cdot M}{t^3}$ ×afloat64 $\frac{L^2 \cdot M}{t^3}$ ×afloat64 $\frac{L^2 \cdot M}{t^3}$ ×sity in three bands.3float64 $\frac{L^2 \cdot M}{t^3}$ ×afloat64 $\frac{L^2 \cdot M}{t^3}$ ×afloat64 $\frac{L^2 \cdot M}{t^3}$ ×	ShapeTypeUnitsSHES6float32dimensionless \checkmark \checkmark mputed in a single iteration from the total mcomponents and one off-diagonal triangle as (hen we have more than 20 particles.3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times afloat64 $\frac{L^2 \cdot M}{t^3}$ \times \times 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times	ShapeTypeUnitsSHESIS6float32dimensionless \checkmark \times \times mputed in a single iteration from the total mass of components and one off-diagonal triangle as (1,1), hen we have more than 20 particles. x \times 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times	ShapeTypeUnitsSHESISEP6float32dimensionless \checkmark \times \times \times \times 6float32dimensionless \checkmark \times \times \times \times mputed in a single iteration from the total mass distributioncomponents and one off-diagonal triangle as (1,1), (2,2),hen we have more than 20 particles.3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times \times 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times \times	ShapeTypeUnitsSHESISEPSO6float32dimensionless \checkmark \times \times \checkmark <	ShapeTypeUnitsSHESISEPSOCategory6float32dimensionless \checkmark \times \times \times \checkmark generalmputed in a single iteration from the total mass distribution, components and one off-diagonal triangle as (1,1), (2,2), (3,3), hen we have more than 20 particles.general3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times \checkmark 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \checkmark \checkmark 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times \checkmark 4generalsity in three bands.Excludes gas in the inner excised core \checkmark 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times \checkmark 4generalsity in three bands. Excludes gas in the inner excised core \checkmark \checkmark \checkmark \checkmark 3float64 $\frac{L^2 \cdot M}{t^3}$ \times \times \times \checkmark \checkmark 4general \checkmark \checkmark \checkmark \checkmark \checkmark \checkmark 5general \checkmark \checkmark \checkmark \checkmark \checkmark \checkmark 4 $=$ $=$ \bullet \checkmark \checkmark \checkmark \checkmark

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AGN.

Name	Shape	Type	Units	SH	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										
XRayLuminosityInRestframe- WithoutRecentAGNHeatingCore- Excision	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
Total rest-frame Xray lumino	osity in th	nree bands	s. Excludes gas t	that v	vas re	cently	y heat	ed by		
AGN. Excludes gas in the inner exc	ised core		Ŭ			·		Ū		
XRayLuminosityWithoutRecent- AGNHeating	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Total observer-frame Xray lu by AGN.	minosity	in three b	ands. Excludes g	gas th	at was	s rece	ntly h	eated		
$XRayLuminosityWithoutRecent-AGNHeatingCoreExcision^{12}$	3	float64	$\frac{L^2 \cdot M}{t^3}$	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Total observer-frame Xray lu by AGN. Excludes gas in the inner	minosity excised c	in three b ore	ands. Excludes g	gas th	at was	s rece	ntly h	eated		
XRayPhotonLuminosity ¹⁸ Total observer-frame Xray pl	3 hoton lur	float64 ninosity ii	1/t n three bands.	×	×	×	×	1	general	$1.36693{\rm e}10 \to 1.367{\rm e}10$
XRayPhotonLuminosityCore- Excision ¹²	3	float64	1/t	×	×	×	×	1	general	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Total observer-frame Xray p excised core	ohoton lu	minosity	in three bands.	Excl	udes	gas ii	n the	inner		

Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
XRayPhotonLuminosityIn- Restframe ¹⁸	3	float64	1/t	×	×	×	×	1	general	$1.36693 e10 \rightarrow 1.367 e10$
Total rest-frame Xray photon	luminos	sity in thr	ee bands.							
XRayPhotonLuminosityIn- RestframeCoreExcision	3	float64	1/t	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
Total rest-frame Xray photon core	luminos	sity in thr	ee bands. Excl	udes g	as in t	the in	nner e	xcised		
XRayPhotonLuminosityIn- RestframeWithoutRecent- AGNHeating	3	float64	1/t	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
heated by AGN.	n lumino	sity in ti	ree bands. Ex	clude	gas ti	nat v	vas re	cently		
XRayPhotonLuminosityIn- RestframeWithoutRecent- AGNHeatingCoreExcision	3	float64	1/t	×	×	×	×	1	general	$1.36693e10 \rightarrow 1.367e10$
	n lumino	osity in th	ree bands. Ex	clude	gas tl	hat v	vas re	cently		
heated by AGN. Excludes gas in the	e inner e	xcised cor	e							

heated by AGN.

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
XRayPhotonLuminosityWithout- RecentAGNHeatingCore- Excision ¹²	3	float64	1/t	×	×	×	×	1	general	$1.36693\mathrm{e}10 ightarrow 1.36'$
Total observer-frame Xray p heated by AGN. Excludes gas in th	hoton lun ne inner e	ninosity ir xcised cor	n three bands. E	xclude	e gas t	that v	vas re	cently		
AngularMomentumGas ¹⁹ Total angular momentum o mass velocity.	3 f the gas,	float32 relative	$L^2 \cdot M/t$ to the centre of	✓ poten	✓ ntial a	✓ .nd g	× as cen	✓ tre of	gas	$1.36693\mathrm{e}10 \rightarrow 1.36'$
DiscToTotalGasMassFraction Fraction of the total gas ma	1 ss that is	float32 co-rotatin	dimensionless ng.	1	1	1	×	1	gas	$1.36693\mathrm{e}10 \rightarrow 1.36'$
GasCentreOfMass Centre of mass of gas.	3	float64	$\mathbf{a}\cdot\mathbf{L}$	×	×	X	×	1	gas	1 pc accurate
GasCentreOfMassVelocity Centre of mass velocity of g	3 as.	float32	$\mathbf{a}\cdot\mathbf{L}/\mathbf{t}$	×	×	×	×	1	gas	0.1 km/s accurate
GasInertiaTensor 3D inertia tensor computed centre. Diagonal components and c Only calculated when we have mor	6 iterativel one off-dia e than 20	float32 y from th gonal tria particles	L^2 e gas mass distrangle as (1,1), (2	✓ ibutio ,2), (3	× on, rel 3,3), ($\begin{array}{c} \times \\ \text{ative} \\ 1,2), \end{array}$	$\begin{array}{c} \times \\ \text{to the} \\ (1,3), \end{array}$	× e halo (2,3).	gas	$1.36693\mathrm{e}10 \rightarrow 1.367$

Description										
GasInertiaTensorNoniterative 3D inertia tensor compute the halo centre. Diagonal comp (1,3), (2,3). Only calculated whe	6 d in a sing onents and n we have	float32 gle iteratio: 1 one off-d more than	L ² n from the gas n iagonal triangle 20 particles.	✓ mass o as (1	× listrib .,1), (2	× ution, 2,2), (× , relat (3,3),	\checkmark tive to $(1,2),$	gas	1.36693 e10 ightarrow 1.367 e10
GasInertiaTensorReduced Reduced 3D inertia tensor the halo centre. Diagonal compe (1,3), (2,3). Only calculated whe	6 computed onents and n we have	float32 l iterativel: l one off-d more than	dimensionless y from the gas r iagonal triangle 20 particles.	✓ mass o as (1	\mathbf{X} listrib	× ution, 2,2), (× , relat (3,3),	$\begin{array}{c} X \\ \text{tive to} \\ (1,2), \end{array}$	gas	1.36693e10 ightarrow 1.367e10
GasInertiaTensorReduced- Noniterative Reduced 3D inertia tensor relative to the halo centre. Diagon (1,2), (1,3), (2,3). Only calculate	6 r compute nal compo d when we	float32 d in a sing nents and o e have mor	dimensionless gle iteration from one off-diagonal e than 20 partic	✓ n the triang cles.	× gas m gle as ($\begin{array}{c} \times \\ \text{mass d} \\ (1,1), \end{array}$	\times listrib (2,2),	✓ oution, (3,3),	gas	1.36693e10 ightarrow 1.367e10
GasProjectedVelocityDispersion ² Mass-weighted velocity dis centre of mass velocity.	⁰ 1 spersion o	float32 f the gas a	L/t long the project	× tion a	× xis, re	× elative	✓ e to tl	X he gas	gas	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
GasVelocityDispersionMatrix ²¹ Mass-weighted velocity disvelocity. The order of the compo	6 spersion o nents of th	float32 f the gas. ne dispersio	$\frac{L^2}{t^2}$ Measured relation tensor is XX	✓ ve to YY Z	× the ga Z XY	× as cen XZ Y	× tre of Z.	× f mass	gas	$1.36693e10 \rightarrow 1.367e10$
$HalfMassRadiusGas^4$	1	float32	$\mathbf{a}\cdot\mathbf{L}$	1	1	1	1	×	gas	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$

Shape Type Units SH ES IS EP SO Category Compression

IalfMassRadiusGas ⁴	1	float32	$\mathbf{a} \cdot \mathbf{L}$	\checkmark	1	1	1	Х	gas	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Gas half mass radius.										

Name

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										

KappaCorotGas²² float32 dimensionless 1 1 1 \checkmark \times Х $1.36693e10 \rightarrow 1.367e10$ gas Kappa-corot for gas, relative to the centre of potential and the centre of mass velocity of the gas. float 64 $\frac{L^2 \cdot M}{t^2}$ KineticEnergyGas²³ 1 Х X $1.36693 {\rm e10} \rightarrow 1.367 {\rm e10}$ gas Total kinetic energy of the gas, relative to the gas centre of mass velocity. ProjectedGasInertiaTensor-3 float32 L² $1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$ Х Х Х 1 Х gas

Noniterative 2D inertia tensor computed in a single iteration from the gas mass distribution, relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2). Only calculated when we have more than 20 particles.

ProjectedGasInertiaTensor-3float32dimensionless \times \times \times \times \times gas1.36693e10 \rightarrow 1.367e10Reduced 2D inertia tensor computed in a single iteration from the gas mass distribution,
relative to the halo centre. Diagonal components and one off-diagonal value as (1,1), (2,2), (1,2).
Only calculated when we have more than 20 particles.00

AngularMomentumDarkMatter¹⁹ 3 float32 $L^2 \cdot M/t$ \checkmark \checkmark \checkmark \checkmark \checkmark dm 1.36693e10 \rightarrow 1.367e10 Total angular momentum of the dark matter, relative to the centre of potential and DM centre of mass velocity.

Name	Shape	Type	Units	SH	\mathbf{ES}	\mathbf{IS}	EP	SO	Category	Compression
Description										
DarkMatterInertiaTensor 3D inertia tensor computed centre. Diagonal components and c Only calculated when we have mor	6 iterativel ne off-dia e than 20	float32 y from th agonal tria particles	L^2 e DM mass distrangle as (1,1), (2	✓ ributic 2,2), (3	× on, rel 3,3), (\mathbf{x} ative 1,2),	$\begin{array}{c} X \\ \text{to the} \\ (1,3), \end{array}$	× e halo (2,3).	dm	$1.36693e10 \rightarrow 1.367e10$
DarkMatterInertiaTensor- Noniterative 3D inertia tensor computed to the halo centre. Diagonal compo- (1,3), (2,3). Only calculated when	6 in a sing onents and we have r	float32 le interati d one off- nore than	L ² ion from the DM diagonal triangle 20 particles.	✓ I mass e as (1	× s distr .,1), (\mathbf{X} ributi $2,2),$	× ion, re (3,3),	\checkmark elative $(1,2),$	dm	$1.36693e10 \rightarrow 1.367e10$
DarkMatterInertiaTensorReduced Reduced 3D inertia tensor of the halo centre. Diagonal compon (1,3), (2,3). Only calculated when	6 omputed ents and we have r	float32 iteratively one off-d nore than	dimensionless y from the DM r iagonal triangle 20 particles.	✓ nass d as (1,	× istrib ,1), (2	\mathbf{X} ution 2,2),	$\mathbf{\times}$, relat $(3,3),$	$\begin{array}{c} X \\ \text{tive to} \\ (1,2), \end{array}$	dm	$1.36693e10 \rightarrow 1.367e10$
DarkMatterInertiaTensor- ReducedNoniterative Reduced 3D inertia tensor correlative to the halo centre. Diagona (1,2), (1,3), (2,3). Only calculated	6 omputed l compon when we	float32 in a singlents and of have mor	dimensionless e interation from one off-diagonal e than 20 partic	✓ n the l triang les.	× DM m le as (× nass c 1,1),	$\begin{array}{c} \times \\ \text{listrib} \\ (2,2), \end{array}$	✓ ution, (3,3),	dm	$1.36693e10 \rightarrow 1.367e10$
DarkMatterProjectedVelocity- Dispersion ²⁰ Mass-weighted velocity dispersion centre of mass velocity.	1 ersion of	float32 the DM a	L/t long the project	× ion ax	× tis, rel	× lative	✓ e to th	× e DM	dm	$1.36693e10 \rightarrow 1.367e10$

		Type	Units	SH	ES	IS	EP	SO	Category	Compression
DarkMatterVelocityDispersion- Matrix ²¹	6	float32	$\frac{L^2}{t^2}$	1	×	×	×	×	dm	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Mass-weighted velocity dis of mass velocity. The order of the	persion of t e componen	the dark name	matter. Measur dispersion tens	ed rela or is X	tive t X YY	o the ZZ I	e DM e XY X	centre Z YZ.		
HalfMassRadiusDarkMatter ⁴ Dark matter half mass rad	1 ius.	float32	$\mathbf{a} \cdot \mathbf{L}$	1	1	1	1	×	dm	$1.36693e10 \rightarrow 1.367e10$
MaximumDarkMatterCircular- Velocity	1	float32	L/t	✓	×	×	×	×	dm	$1.36693e10 \rightarrow 1.367e10$
ticle softening lengths	calculated	using da	rk matter parti	cies wii	en aco	count	ing io	r par-		
MaximumDarkMatterCircular- VelocityRadius	1	float32	a · L	1	×	×	×	×	dm	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
Radius at which Maximum	nDarkMatte	erCirculai	rVelocity is read	ched.						
$Angular Momentum Stars^{19}$	3 of the stars	float32 relative	$L^2 \cdot M/t$ to the centre of	✓ of poter	✓ ntial a	✓ und_st	X tellar (✓ centre	star	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$

Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
KappaCorotStars ²² Kappa-corot for stars, relat the stars.	1 ive to the	float32 centre of	dimensionless potential and th	✓ ne cen	✓ tre of	✓ mass	× s veloo	× city of	star	$1.36693 e10 \rightarrow 1.367 e10$
KineticEnergyStars ²³ Total kinetic energy of the s	1 stars, rela	float64 tive to the	$\frac{\underline{L^2 \cdot M}}{t^2}$ e stellar centre o	× of mas	✓ s velo	✓ city.	×	1	star	$1.36693 {\rm e}{\rm 10} \rightarrow 1.367 {\rm e}{\rm 10}$
LuminosityWeightedMeanStellar- Age Luminosity weighted mean	1 stellar age	float32 e. The we	t ight is the r ban	✓ .d lum	✓ inosit	✓ y.	×	×	star	$1.36693e10 \rightarrow 1.367e10$
MassWeightedMeanStellarAge Mass weighted mean stellar	1 age.	float32	t	1	1	1	×	×	star	$1.36693e10 \rightarrow 1.367e10$
ProjectedStellarInertiaTensor- Noniterative 2D inertia tensor computed to the halo centre. Diagonal comp calculated when we have more tha	3 in a singl ponents a n 20 part	float32 le iteration nd one of icles.	L ² n from the stella f-diagonal value	× as (1	× s dist ,1), (2	× ribut: 2,2),	✓ ion, re (1,2).	× elative Only	star	$1.36693e10 \rightarrow 1.367e10$
ProjectedStellarInertiaTensor- ReducedNoniterative Reduced 2D inertia tensor c relative to the halo centre. Diagon	3 omputed al compo	float32 in a single nents and	dimensionless e iteration from t one off-diagona	× the ste l value	× ellar m e as (× nass c 1,1),	\checkmark listrib $(2,2),$	× ution, (1,2).	star	$1.36693e10 \rightarrow 1.367e10$

Only calculated when we have more than 20 particles.

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Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										
StellarCentreOfMass Centre of mass of stars.	3	float64	$\mathbf{a} \cdot \mathbf{L}$	×	1	1	×	1	star	1 pc accurate
StellarCentreOfMassVelocity Centre of mass velocity of st	3 ars.	float32	$\mathbf{a}\cdot\mathbf{L}/\mathbf{t}$	×	1	1	×	1	star	$0.1~{\rm km/s}$ accurate
StellarInertiaTensor 3D inertia tensor computed halo centre. Diagonal components (2,3). Only calculated when we have	6 iterative and one over more th	float32 ly from t off-diagon han 20 pa	L^2 he stellar mass al triangle as (1 rticles.	✓ distrik ,1), (2	\mathbf{x} pution $(2,2), (3)$	× , rela 3,3),	$\begin{array}{c} X \\ \text{ative t} \\ (1,2), \end{array}$	(1,3),	star	$1.36693e10 \rightarrow 1.367e10$
StellarInertiaTensorNoniterative 3D inertia tensor computed to the halo centre. Diagonal compo- (1,3), (2,3). Only calculated when y	6 in a singl onents and we have r	float32 e iteration d one off- nore than	L ² n from the stella diagonal triangle 20 particles.	✓ ar mas e as (1	× s distr .,1), (2	\mathbf{X} ributi 2,2),	$\begin{array}{c} \times \\ \text{ion, re} \\ (3,3), \end{array}$	\checkmark lative $(1,2),$	star	$1.36693e10 \rightarrow 1.367e10$
StellarInertiaTensorReduced Reduced 3D inertia tensor co to the halo centre. Diagonal compo- (1,3), (2,3). Only calculated when y	6 omputed onents and we have r	float32 iteratively d one off- nore than	dimensionless y from the stella diagonal triangle 20 particles.	✓ ar mas e as (1	× s distr .,1), (2	\mathbf{X} ributi 2,2),	× ion, re (3,3),	$\begin{array}{c} X \\ \text{lative} \\ (1,2), \end{array}$	star	$1.36693e10 \rightarrow 1.367e10$
StellarInertiaTensorReduced- Noniterative Reduced 3D inertia tensor co relative to the halo centre. Diagonal	6 omputed i l compone	float32 in a single ents and o	dimensionless iteration from to one off-diagonal	✓ the ste	× llar m le as (× nass d 1,1),	$\begin{array}{c} \times \\ \text{listrib} \\ (2,2), \end{array}$	✓ ution, (3,3),	star	$1.36693e10 \rightarrow 1.367e10$

(1,2), (1,3), (2,3). Only calculated when we have more than 20 particles.

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Name Description	Shape	Type	Units	SH	ES	IS	EP	SO	Category	Compression
StellarInitialMass Total stellar initial mass.	1	float32	М	1	1	1	1	1	star	$1.36693 e10 \rightarrow 1.367 e10$
StellarLuminosity ²⁴ Total stellar luminosity in t	9 he 9 GAN	float32 /IA bands	dimensionless	1	1	1	1	1	star	$1.36693 \mathrm{e}10 ightarrow 1.367 \mathrm{e}10$
StellarMassFractionInIron Total stellar mass fraction i	1 n iron.	float32	dimensionless	×	1	1	×	1	star	$1.36693e10 \rightarrow 1.367e10$
StellarMassFractionInOxygen Total stellar mass fraction i	1 n oxygen.	float32	dimensionless	×	1	1	×	1	star	$1.36693e10 \rightarrow 1.367e10$
StellarProjectedVelocity- Dispersion ²⁰ Mass-weighted velocity disp stellar centre of mass velocity.	1 persion of	float32 E the stars	L/t s along the proj	×	× axis	× , rela	✓ ative f	× to the	star	$1.36693e10 \rightarrow 1.367e10$
StellarVelocityDispersionMatrix ²¹ Mass-weighted velocity disp mass velocity. The order of the co	6 persion of mponents	float32 the stars of the dis	$\begin{array}{c} \frac{L^2}{t^2}\\ . & Measured rela\\ spersion tensor is \end{array}$	✓ tive t	× o the YY Z	× stella Z XY	× ar cen XZ Y	× tre of YZ.	star	$1.36693e10 \rightarrow 1.367e10$
AngularMomentumBaryons ¹⁹ Total angular momentum of baryonic centre of mass velocity.	3 f baryons	float32 (gas and s	$L^2 \cdot M/t$ stars), relative to	✓ o the o	✓ centre	✓ of po	×	✓ al and	baryon	$1.36693e10 \rightarrow 1.367e10$
HalfMassRadiusBaryons Baryonic (gas and stars) ha	1 lf mass ra	float32 idius.	$\mathbf{a} \cdot \mathbf{L}$	1	1	1	1	×	baryon	$1.36693e10 \rightarrow 1.367e10$

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	IS	\mathbf{EP}	SO	Category	Compression
Description										

KappaCorotBaryons ²² Kappa-corot for baryo	1 ons (gas and st	float32 tars), relat	dimensionless ive to the centre	✓ of p	✓ otentia	✓ al and	× i the	\mathbf{x}	baryon	$1.36693\mathrm{e}10 \rightarrow 1.3$
of mass velocity of the baryon	ns.									
HaloCatalogueIndex Index of this halo in t	1 he original hal	int64 o finder ca	dimensionless talogue (first ha	× lo ha	× s inde	X x=0).	×	×	Input	no compression
HaloCentre The centre of the sub positions. For VR and HBT subhalo.	3 halo as given plus this is ec	float64 by the ha qual to the	a · L lo finder. Used position of the	× as re most	× eferenc boun	× ce for id pai	× all r rticle	× elative in the	Input	1 pc accurate
IsCentral Whether the halo find	1 er flagged the	int64 halo as ce	dimensionless ntral (1) or satel	× lite (× 0).	×	×	×	Input	no compression
NumberOfBoundParticles Total number of partic	1 cles bound to	int64 the subhal	dimensionless o.	×	×	×	×	×	Input	no compression
Depth Level of the subhalo in	1 n the merging	uint64 hierarchy.	dimensionless	×	×	×	×	×	HBTplus	no compression
DescendantTrackId TrackId of the descend	1 lant of this su	int64 bhalo.	dimensionless	×	×	×	×	×	HBTplus	no compression
HostFOFId	1	int64	dimensionless	×	X	×	X	×	HBTplus	no compression

Name	Shape	Type	Units	SH	\mathbf{ES}	\mathbf{IS}	\mathbf{EP}	SO	Category	Compression
Description										
LastMaxMass	1	float32	М	×	×	×	×	×	HBTplus	$1.36693e10 \rightarrow 1.367e10$
Maximum mass of this subh	alo across	s its evolu	tionary history						Ŧ	
LastMaxVmaxPhysical	1	float32	L/t	×	×	×	×	×	HBTplus	$1.36693 e10 \rightarrow 1.367 e10$
Largest value of maximum of	circular ve	elocity of	this subhalo acro	oss its	evolu	ltiona	ary his	story		
NestedParentTrackId	1	int64	dimensionless	×	×	x	×	×	HBTplus	no compression
TrackId of the parent of this	s subhalo.								F - 000	
SnapshotIndexOfBirth	1	int64	dimensionless	×	x	x	×	×	HBTplus	no compression
Snapshot when this subhalo	was form	ned.							F - 000	···
SnapshotIndexOfLastMaxMass	1	uint64	dimensionless	×	×	x	×	×	HBTplus	no compression
Latest snapshot when this s	ubhalo ha	its max	ximum mass.						ing r brag	
SnapshotIndexOfLastMaxVmax	1	uint64	dimensionless	×	×	x	×	×	HBTplus	no compression
Latest snapshot when this s	ubhalo ha	d its larg	est maximum cir	rcular	veloc	ity.			iib i piùo	
TrackId	1	uint64	dimensionless	×	×	x	×	×	HBTplus	no compression
Unique ID for this subhalo	which is c	onsistent	across snapshots	3.					IID I pius	no compression
Contras	9	floot 6 4	- I	~	\sim	\sim	~	~	EOE	1 no occurato
Centres Centre of mass of the host F	э OF halo o	f this sub	a·L halo. Zero for sat	^	∧ and h	∧ ostle	∧ ss sub	∧ halos.	гОг	1 pc accurate
	or naio o	1 1110 540.			and n	.00010	00 000	iiaiob.		
Masses	1	float32	Μ	×	×	×	×	×	FOF	$1.36693 {\rm e10} \rightarrow 1.367 {\rm e10}$
Mass of the host FOF halo of this subhalo. Zero for satellite and hostless subhalos.										

Name	Shape	Type	Units	\mathbf{SH}	\mathbf{ES}	IS	\mathbf{EP}	SO	Category	Compression
Description										

Sizes	1	uint64	dimensionless	×	\times	×	X	×	FOF	no compression
Number of particles in the	ne host FO	F halo of	this subhalo. Ze	ero fo	r satel	lite a	and h	ostless		
subhalos.										
HostHaloIndex Index (within the SOAF subhalos.	1 ' arrays) o	int64 f the top	dimensionless level parent of t	× his s	× ubhalo	×)1	× for a	× central	SOAP	no compression
${\rm IncludedInReducedSnapshot}$	1	int32	dimensionless	×	×	×	×	×	SOAP	no compression

Whether this halo is included in the reduced snapshot.

SubhaloRankByBoundMass 1 int32 dimensionless × × × × × SOAP no compression Ranking by mass of the halo within its parent field halo. Zero for the most massive halo in the field halo.

5 Non-trivial properties

¹The centre of mass and centre of mass velocity are computed using all particle types except neutrinos (since neutrinos can never be bound to a halo).

²The concentration is computed using the method described in Wang et al. (2023), but using a fifth order polynomial fit to the R1-concentration relation for 1 < c < 1000. Therefore we set a floor of 1 and a ceiling of 1000 for the values calculated by SOAP. This method assumes halos have an NFW profile, and is only calculated for the following SO variations: 200_{crit} , 200_{mean} , and BN98. Neutrinos are included in the calculation of total concentration. The first moment of the density distribution, R1, can be estimated from the concentration. From R1 the Einasto concentration can be calculated. It also possible to estimate other properties, such as V_{max} , by using the R1 value and assuming an NFW profile.

³The oxygen and iron masses are computed from SmoothedElementMassFractions and not ElementMassFractions, since the latter were not output in the FLAMINGO snapshots. Metal mass fractions on the other hand are based on MetalMassFractions.

⁴**The half mass radius** is determined from linear interpolation of the cumulative mass profile obtained after sorting all particles by radius. For the projected halos (PA), SOAP uses the 2D radius (distance to the projection axis) instead of the 3D radius.

⁵The maximum circular velocity and the radius where it is reached are computed using

$$v_{\max} = \sqrt{\frac{GM(\le r)}{r}},\tag{1}$$

where the cumulative mass $M(\leq r)$ includes all particles within the radius r, and includes the contribution of the particle(s) at r = 0. The radius is computed relative to the centre of potential. The softened v_{\max} value is calculated using the same method, except the particle radius has a floor of the softening length. An alternative way to calculate v_{\max} is to estimate it from the halo concentration by assuming an NFW profile. We store the radius of the unsoftened maximum circular velocity. If the softened and unsoftened maximum circular velocities are equal, then their radii will also be equal. If the values are not equal, then the radius of the softened maximum circular velocity will be the simulation softening length.

⁶The most massive black hole is identified based on the BH subgrid mass (i.e. the same mass that goes into BlackHolesSubgridMass).

⁷The neutrino masses exist in two flavours. RawNeutrinoMass is obtained by simply summing the neutrino particle masses, while the noise suppressed version, NoiseSuppressedNeutrinoMass is defined as

$$M_{\nu,\rm NS} = \sum_{i} m_i w_i + \frac{4\pi}{3} \rho_{\nu} R_{\rm SO}^3, \qquad (2)$$

where w_i are the neutrino weights (which can be negative), and ρ_{ν} is the background density of neutrinos that is also used in the SO radius calculation. The latter is obtained from the snapshot header.

⁸When distinguishing between star-forming and non star-forming gas and computing the total star formation rate, we have to be careful about the interpretation of the StarFormationRates dataset in the snapshots, since negative values in that dataset are used to store another quantity, the last scale factor when that particular gas particle was star-forming. Star-forming gas is then gas for which StarFormationRates is strictly positive, and the total star formation rate is the sum of only the strictly positive values.

⁹The Compton y parameter is computed as in McCarthy et al. (2017):

$$y = \sum_{i} \frac{\sigma_T}{m_e c^2} n_{e,i} k_B T_{e,i} \frac{m_i}{\rho_i},\tag{3}$$

where σ_T is the Thomson cross section, m_e the electron mass, c the speed of light and k_B the Boltzmann constant. $n_{e,i}$ and $T_{e,i}$ are the electron number density and electron temperature for gas particle i, while $V_i = m_i/\rho_i$ is the SPH volume element that turns the sum over all particles i within the inclusive sphere into a volume integral. Note that the snapshot already contains the individual y_i values for the SPH particles, computed from the cooling tables during the simulation.

¹⁰**The Doppler B parameter** is computed as in Roncarelli et al. (2018):

$$b = \frac{\sigma_T}{c} \sum_i n_{e,i} v_{r,\text{obs},i} \frac{m_i}{\rho_i A_{\text{obs}}},\tag{4}$$

where σ_T is the Thomson cross section, c the speed of light, $n_{e,i}$ the electron number density for gas particle i, with $V_i = m_i/\rho_i$ the corresponding SPH particle volume. The relative *peculiar* velocity is taken relative to the box and along a line of sight towards a particular observer, so

$$v_{r,\text{obs},i} = \vec{v}_i \cdot \frac{(\vec{x}_i - \vec{x}_{\text{obs}})}{|\vec{x}_i - \vec{x}_{\text{obs}}|},\tag{5}$$

with \vec{x}_i and \vec{v}_i the physical position and velocity of particle *i*, and \vec{x}_{obs} the arbitrary observer position.

The surface area A_{obs} that turns the volume integral into a line integral is that of the aperture for which b is computed, i.e. $A_{\text{obs}} = \pi R_{\text{SO}}^2$.

As the observer position we use the position of the observer for the first lightcone in the simulation, or the centre of the box if no lightcone was present. This choice is arbitrary and can be adapted. Since \vec{x}_{obs} can in principle coincide with \vec{x}_i , we make sure $v_{r,obs,i}$ is set to zero in this case to avoid division by zero.

¹¹The Compton Y-weighted temperature is computed as

$$T = \frac{1}{\sum_{i} y_i} \sum_{i} y_i T_i,\tag{6}$$

¹²Core excised quantities Excludes the inner region of the halo when computing the quantity. It is only calculated for $SO/5OO_crit$. Any core excised calculation only uses the particles for which

$$0.15R_{500c} \le \mathbf{r} \ge R_{500c} \tag{7}$$

¹³The mass-weighted temperature is computed as

$$T = \frac{1}{\sum_{i} m_i} \sum_{i} m_i T_i, \tag{8}$$

and the GasTemperatureWithoutRecentAGNHeating variant uses the same definition, but excludes particles that satisfy

$$\texttt{LastAGNFeedbackScaleFactors}_i \ge a - 15 \text{Myr} \tag{9}$$

and

$$0.1\Delta T_{\rm AGN} \le T_i \le 10^{0.3} \Delta T_{\rm AGN},\tag{10}$$

using the same parameters as used internally by SWIFT and with a the current scale factor.

¹⁴The satellite mass fractions is obtained by summing the masses of all particles within the inclusive sphere that are bound to a subhalo that is not the central subhalo, and dividing this by $M_{\rm SO}$. This uses the same membership information that is also used to decide what particles need to be included in the exclusive sphere and projected aperture properties. For MassFractionSatellites we only consider particles with the same FOF ID as the most bound particle in the central subhalo. For MassFractionExternal we include all particles with a FOF ID not equal to the most bound particle in the central subhalo.

¹⁵The spectroscopic-like temperature is computed as

$$T_{SL} = \frac{\sum_{i} \rho_{i} m_{i} T_{i}^{1/4}}{\sum_{i} \rho_{i} m_{i} T_{i}^{-3/4}}$$
(11)

¹⁶**The spin parameter** is computed following Bullock et al. (2021):

$$\lambda = \frac{|\vec{L}_{\text{tot}}|}{\sqrt{2}Mv_{\text{max}}R},\tag{12}$$

where \vec{L}_{tot} is the total angular momentum of all particles within radius R, and M their total mass. The angular momentum is computed relative to the centre of potential and the total centre of mass velocity. Since subhalos do not have a natural radius associated with them, we use the radius where the softened v_{max} is reached.

¹⁷**The thermal energy** of the gas is computed from the density and pressure, since the internal energy was not output in the FLAMINGO snapshots. The relevant equation is

$$u = \frac{P}{(\gamma - 1)\rho},\tag{13}$$

with $\gamma = 5/3$.

¹⁸X-ray quantities are computed directly from the X-ray datasets in the snapshot. They are either in the emission rest-frame, or in the observed-frame of a z = 0 observer, using the redshift of the snapshot as the emission redshift . The three bands are always given in the same order as in the snapshot:

- 1. eRosita low/soft (0.2 2.3 keV)
- 2. eRosita high/hard (2.3 8 keV)
- 3. ROSAT (0.5 2 keV)

¹⁹**The angular momentum** of gas, dark matter and stars is computed relative to the centre of potential (cop) and the centre of mass velocity of that particular component, and not to to the total centre of mass velocity. The full expression is

$$\vec{L}_{\text{comp}} = \sum_{i=\text{comp}} m_i \left(\vec{x}_{r,i} \times \vec{v}_{\text{comp},r,i} \right), \qquad (14)$$

with the sum i over all particles of that particular component (bound to the halo), and

$$\vec{x}_{r,i} = \vec{x}_i - \vec{x}_{\rm cop},\tag{15}$$

$$\vec{v}_{\text{comp},r,i} = \vec{v}_i - \vec{v}_{\text{com,comp}},\tag{16}$$

where

$$\vec{v}_{\rm com,comp} = \frac{\sum_{i=\rm comp} m_i \vec{v}_i}{\sum_{i=\rm comp} m_i}.$$
(17)

For FLAMINGO, we also compute the angular momentum for baryons, where the sum is then over both gas and star particles.

 20 **The projected velocity dispersion** is computed along the projection axis. Along this axis, the velocity is a 1D quantity, so that the velocity dispersion is simply 1 value.

²¹The velocity dispersion matrix is defined as

$$V_{\text{disp,comp}} = \frac{1}{\sum_{i=\text{comp}} m_i} \sum_{i=\text{comp}} m_i \vec{v}_{\text{comp},r,i} \vec{v}_{\text{comp},r,i}, \qquad (18)$$

where we compute the relative velocity as before, i.e. w.r.t. the centre of mass velocity of the particular component of interest. While it is strictly speaking a 3×3 matrix, there are only 6 independent components. We use the following convention to output those 6 components as a 6 element array:

$$V'_{\rm disp} = \begin{pmatrix} V_{xx} & V_{yy} & V_{zz} & V_{xy} & V_{xz} & V_{yz} \end{pmatrix}.$$
 (19)

Other velocity dispersion definitions can be derived from this general form. The one-dimensional velocity dispersion can be calculated as

$$\sigma = \sqrt{\frac{V_{xx} + V_{yy} + V_{zz}}{3}} \tag{20}$$

 $^{22}\kappa_{\text{corot}}$ is computed as in Correa et al. (2017):

$$\kappa_{\rm corot, comp} = \frac{K_{\rm corot, comp}}{K_{\rm comp}},\tag{21}$$

with the kinetic energy given by

$$K_{\rm comp} = \frac{1}{2} \sum_{i=\rm comp} m_i |\vec{v}_{\rm comp,r,i}|^2, \qquad (22)$$

the corotational kinetic energy given by

$$K_{\text{corot,comp}} = \sum_{i=\text{comp}} \begin{cases} K_{\text{rot,comp},i}, & L_{\text{comp},p,i} > 0, \\ 0, & L_{\text{comp},p,i} \le 0, \end{cases}$$
(23)

the corotational kinetic energy given by

$$K_{\text{corot,comp}} = \sum_{i=\text{comp}} \begin{cases} K_{\text{rot,comp},i}, & L_{\text{comp},p,i} > 0, \\ 0, & L_{\text{comp},p,i} \le 0, \end{cases}$$
(24)

the rotational kinetic energy given by

$$K_{\text{rot,comp},i} = \frac{1}{2} \frac{L_{\text{comp},p,i}^2}{m_i R_i^2},\tag{25}$$

the projected angular momentum along the angular momentum direction given by

$$L_{\text{comp},p,i} = \vec{L}_i \frac{\vec{L}_{\text{comp}}}{|\vec{L}_{\text{comp}}|},\tag{26}$$

and the orthogonal distance to the angular momentum vector given by

$$R_{i}^{2} = |\vec{x}_{r,i}|^{2} - \left(\vec{x}_{r,i} \frac{\vec{L}_{\rm comp}}{|\vec{L}_{\rm comp}|}\right),$$
(27)

where the angular momentum vector and the relative position and velocity are the same as above for consistency.

 23 The kinetic energy of the gas and stars is computed using the same relative velocities as used for other properties, i.e. relative to the centre of mass velocity of the gas and stars respectively.

²⁴Luminosities are given in the GAMA bands and are always using the same order as in the snapshots: u, g, r, i, z, Y, J, H, K. These are restframe dust-free AB-luminosities of the star particles. These were computed using the BC03 (GALAXEV) models convolved with different filter bands and interpolated in log-log ($f(\log(Z), \log(age)) = \log(flux)$) as used in the dust-free modelling of Trayford et al. (2015). The luminosities are given in dimensionless units. They have been divided by 3631 Jy already, i.e. they can be turned into absolute AB-magnitudes (rest-frame absolute maggies) directly by applying -2.5 log10(L) without additional corrections.

6 Spherical overdensity calculations

The radius at which the density reaches a certain threshold value is found by linear interpolation of the cumulative mass profile obtained after sorting the particles by radius. The approach we use is different from that taken by VR, where both the mass and the radius are obtained from independent interpolations on the mass and density profiles (the latter uses the logarithm of the density in the interpolation). The VR approach is inconsistent, in the sense that the condition



Figure 1: Density profile (top row) and cumulative mass profile (bottom row) for an example halo in a 400 Mpc FLAMINGO box. The orange lines show ρ_{target} and R_{SO} and M_{SO} as determined by SOAP, while the green line is the cumulative mass profile at fixed ρ_{target} . The two left columns correspond to a run where R_{SO} is fixed by interpolating on the density profile (so in the top row plot), while the second two columns determine R_{SO} by interpolating on the cumulative mass in the bottom row plots. The right column for each pair of columns shows a zoom of the left column.

$$\frac{4\pi}{3}R_{\rm SO}^3\rho_{\rm target} = M_{\rm SO},\tag{28}$$

is not guaranteed to be true, and will be especially violated for large radial bins (the bins are generated from the particle radii by sorting the particles, so we have no control over their width). We instead opt to guarantee this condition by only finding $R_{\rm SO}$ or $M_{\rm SO}$ by interpolation and using eq. (28) to derive the other quantity.

While the interpolation of the logarithmic density profile to find $R_{\rm SO}$ is more straightforward, we found that it can lead to significant deviations between the value of $M_{\rm SO}$ and the cumulative mass in neighbouring bins that can be more than one particle mass, as illustrated in Fig. 1. The reason for this is that the cumulative mass profile at fixed density increases very steeply with radius, so that a small difference in $R_{\rm SO}$ leads to a relatively large difference in $M_{\rm SO}$. Conversely, fixing $M_{\rm SO}$ will lead to an $R_{\rm SO}$ that only deviates a little bit from the $R_{\rm SO}$ found by interpolating the density profile. However, doing so requires us to find the intersection of the cumulative mass profile at fixed density (green line in Fig. 1) with the actual cumulative mass profile, which means solving the following equation:

$$\frac{4\pi}{3}\rho_{\text{target}}R_{\text{SO}}^3 = M_{\text{low}} + \left(\frac{M_{\text{high}} - M_{\text{low}}}{R_{\text{high}} - R_{\text{low}}}\right) \left(R_{\text{SO}} - R_{\text{low}}\right), \tag{29}$$

where $R/M_{\rm low/high}$ are the bounds of the intersecting bin (which we find in the density profile). This third degree polynomial equation has no unique solution, although in practice only one of the three possible complex solutions is real. We find this solution by using a root finding algorithm within the intersecting bin (we use Brent's method for this).

For clarity, this is the full set of rules for determining the SO radius in SOAP:

- 1. Sort particles according to radius and construct the cumulative mass profile.
- 2. Discard any particles at zero radius, since we cannot compute a density for those. The mass of these particles is used as an r = 0 offset for the cumulative mass profile. Since the centre of potential is the position of the most bound particle, there should always be at least one such particle.
- 3. Construct the density profile by dividing the cumulative mass at every radius by the volume of the sphere with that radius.
- 4. Find intersection points between the density profile and the target density, i.e. the radii $R_{1,2}$ and masses $M_{1,2}$ where the density profile goes from above to below the threshold:
 - (a) If there are none, analytically compute $R_{\rm SO} = \sqrt{3}M_1/(4\pi R_1 \rho_{\rm target})$, where R_1 and M_1 are the first non zero radius and the corresponding cumulative mass. This is a special case of Eq. (29). Unless there are multiple particles at the exact centre of potential position, this radius estimate will then be based on just two particles.
 - (b) In all other cases, we use $R_{1,2}$ and $M_{1,2}$ as input for Eq. (29) and solve for R_{SO} . The only exception is the special case where $R_1 = R_2$. If that happens, we simply move further down the line until we find a suitable interval.
- 5. From $R_{\rm SO}$, we determine $M_{\rm SO}$ using Eq. (28).

Neutrinos – if present in the model – are included in the inclusive sphere calculation (and only here, since neutrino particles cannot be bound to a halo) by adding both their weighted masses (which can be negative), as well as the contribution from the background neutrino density. The latter is achieved by explicitly adding the cumulative mass profile at constant neutrino density to the total cumulative mass profile before computing the density profile. This is the only place where neutrinos explicitly enter the algorithm, except for the neutrino masses computed for the SOs. Neutrinos are not included in the calculation of the centre of mass and centre of mass velocity.

7 Group membership files

Before SOAP can be run we generate a set of files which contain halo membership information for each particle in the SWIFT snapshot. The datasets in these files are stored in the same order and with the same partitioning between files as the datasets in the snapshots. This allows SOAP to read halo membership information for sub-regions of the simulation volume without reading the full halo-finder output. These files may also be useful for visualising the input halo catalogue.

The group membership files are HDF5 files with one group for each particle type, named PartType0, PartType1, ... as in the snapshots. Each group contains the following datasets:

- 1. GroupNr_bound: for each particle in the corresponding snapshot file this contains the array index of the subhalo which the particle is bound to. If a particle is not bound to any subhalo it will have GroupNr_bound=-1.
- 2. Rank_bound: the ranking by total energy of this particle within the subhalo it belongs to, or -1 if the particle is not bound to any subhalo. The particle with the most negative total energy has Rank_bound=0.
- 3. GroupNr_all: (VELOCIraptor only) for each particle in the corresponding snapshot file this contains the array index of the VR group which the particle belongs to, regardless of whether it is bound or unbound. Particles in no group have GroupNr_all=-1.
- 4. FOFGroupIDs: the 3D FOF group the particle is part of. This field is only present if a FOF snapshot is listed in the parameter file. This field is present in the snapshots themselves, but for FLAMINGO hydro simulations the FOF was regenerated. If this field is present it will overwrite the value from the snapshots when SOAP is run.

The GroupNr values stored here are zero based array indexes into the full subhalo catalogue, and not the subhalos IDs. For example the first group in the VELOCIraptor catalogue has GroupNr=0 and ID=1.

The script 'make_virtual_snapshot.py' will combine snapshot and group membership files into a single virtual snapshot file. This virtual file can be read by swiftsimio and gadgetviewer to provide halo membership information alongside other particle properties. Using the virtual file along with the spatial masking functionality within swiftsimio means it is possible to quickly load all the particles bound to a given subhalo.